ELSEVIER
Available online at www.sciencedirect.com
SciVerse ScienceDirect
Procedia IUTAM 8 (2013) 103 – 110
Procedia IUTAM
www.elsevier.com/locate/procedia

IUTAM Symposium on Waves in Fluids: Effects of Nonlinearity, Rotation, Stratification and Dissipation

# Laboratory Study of Horizontal Mixing Process between Two River Plumes at the Sea Shelf (with an Application to the Kara Sea)

D.N. Elkin, V.V. Kremenetskiy, A.G. Zatsepin

*Shirshov Institute of Oceanology, Russian Academy of Sciences*

**Abstract**

The area of about 40000 km$^2$ of desalinated upper layer waters with a salinity less than 25 psu was found during cruise 54 of R/V *Akademik Mstislav Keldysh* in the southwestern part of the Kara Sea (September 2007). The thickness of the desalinated layer was about 10 m and it was separated from underlying marine waters with salinity more than 30 psu by strong density interface. It is likely that initial formation of this layer occurred in June when the flood of the Yenisei and Ob' rivers inflowing into the Kara Sea at the same geographical region was maximal. The results of chemical analysis of water samples taken from this layer in different parts of the desalinated area revealed that the proportions of the content of Ob' and Enisey waters in the samples are different. It means that the horizontal mixing process between the interacting Ob' and Yenisei plumes in the Kara Sea is not completed even after 3 – 4 months after their formation. Laboratory experiments focusing on investigation of horizontal mixing process between two interacting fresh water plumes at the surface of saline water layer were fulfilled in the tank displaced on the rotating platform to reproduce the effects of Earth rotation. It is found that the horizontal mixing efficiency decreases with the increase of platform rotation rate. The estimate of mixing timescale based on laboratory results give the evidence that 3 – 4 months are not enough for the complete horizontal mixing of Ob' and Yenisei river plumes.


Selection and/or peer-review under responsibility of Yuli Chashechkin and David Dritschel

*Keywords:* Kara Sea, Ob' and Yenisei river plumes, horizontal mixing, laboratory study.

## 1. Introduction

Ob' and Yenisei are the two of three largest Siberian rivers enter the Kara sea. The river mouths are located no so far from each other: at the distance of about 200 km. Therefore Ob' and Yenisei river plumes interact actively, especially, during the flood time (June), when about one third of the annual river runoff enters the sea [1] (Fig.1). At that time the Kara Sea upper desalinated layer (UDL) begins to form. This layer has a thickness about 10 m and its salinity is 15 – 25 g/kg and it is separated from underlying marine waters with salinity more than 30 g/kg by strong density interface. (Fig. 2). Basically due to the wind drag this layer spreads over the Kara Sea area and in September-October it covers a large part of it [2] (Fig. 3). Because of the great salinity (density) difference between UDL and underlying layer of marine waters the turbulent exchange across the density jump is very low. Thus, the average salinity and thickness of the UDL

Corresponding autor tel +74991246392; fax +74991245983

Email dmelkin@mail.ru

2210-9838 
Selection and/or peer-review under responsibility of Yuli Chashechkin and David Dritschel
doi:10.1016/j.piutam.2013.04.014

does not change much with time. On the other hand the chemical analysis of water samples taken from the UDL have shown that the proportion in the content of Ob' and Yenisei waters in UDL is changed from one geographical point to the other [3]. That means that the UDL waters are not well horizontally mixed. Two questions arise.

1) what physical mechanism is responsible for horizontal mixing between Ob' and Yenisei plumes?

2) what is the timescale for reaching by UDL horizontally homogeneous state taking into account not only physical, but its chemical properties?

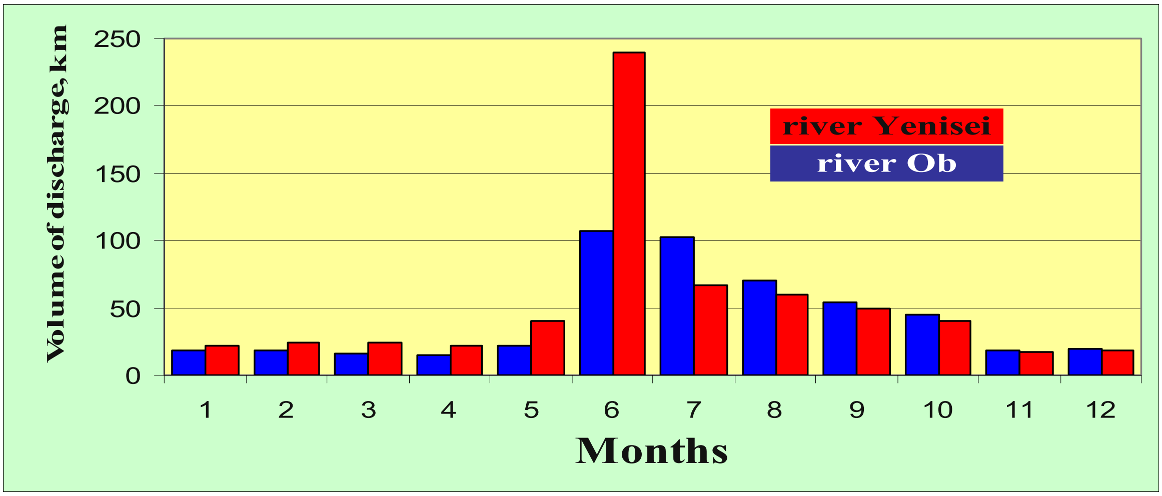


Fig. 1. The annual river runoff into the Kara Sea (from [2]).

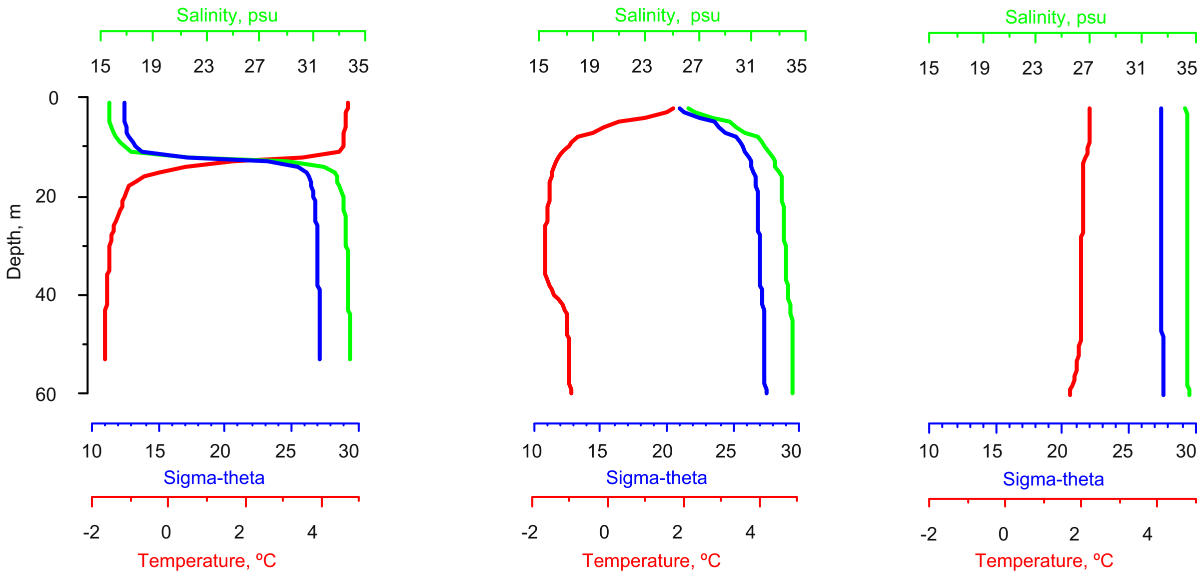


Fig. 2. Vertical distribution of temperature, salinity and density in the regions with UDL (left), at the edge of UDL (middle), without UDL (right).

The analysis of satellite images of the Kara Sea in IR and visible bands of spectrum revealed that Ob' and Yenisei plumes consist of mesoscale eddies with a diameter about 20 – 40 km. An orbital velocity in eddies is about 10 – 20 cm/s and each of them interact actively with the neighboring eddies [2]. We suppose that the horizontal mixing between the river plumes is produced by these eddies and this mixing occurs in the area which radios is $R_0$. Then it is possible to estimate the value of the horizontal mixing coefficient $K$, using a formula: $K=(<U^2>)^{0.5}R_d$, where $R_d = (g'H)/f$ – baroclinic radius of deformation, $g' = g\Delta\rho/\rho$ – reduced acceleration of gravity force, $\Delta\rho$ – density difference between UDL and underlying marine waters, $\rho$ – density of marine waters, $H$ – the depth of the sea shelf, $f=2\Omega\sin\varphi$ –

the Coriolis parameter, $\boldsymbol{\Omega}$ – angular velocity of Earth rotation, $\boldsymbol{\varphi}$ – the latitude angle and $(<U^2>)^{0.5}$ – scale of velocity pulsations in the mesoscale eddy field [4]. Taking the determined values for $R_d \approx 20$ km, and $(<U^2>)^{0.5} \approx 0.14$ m/s we obtain $K \approx 3\times10^3$ m$^2$/s for area of Ob' – Yenisei estuary. Using this value it is possible to estimate mixing timescale $T_m$ in "diffusive" model approximation: $T_m \approx R_0^2/2K \approx 1.3\cdot10^7$s $\approx$ 5 month, or 150 days if $R_0 = 200$ km. That means that the Ob' and Yenisei river plumes should not be well mixed horizontally in 3 – 4 months and reach horizontally homogeneous state till the end of warm season (September – October). However these hypothesis and estimates could be checked by laboratory modeling.

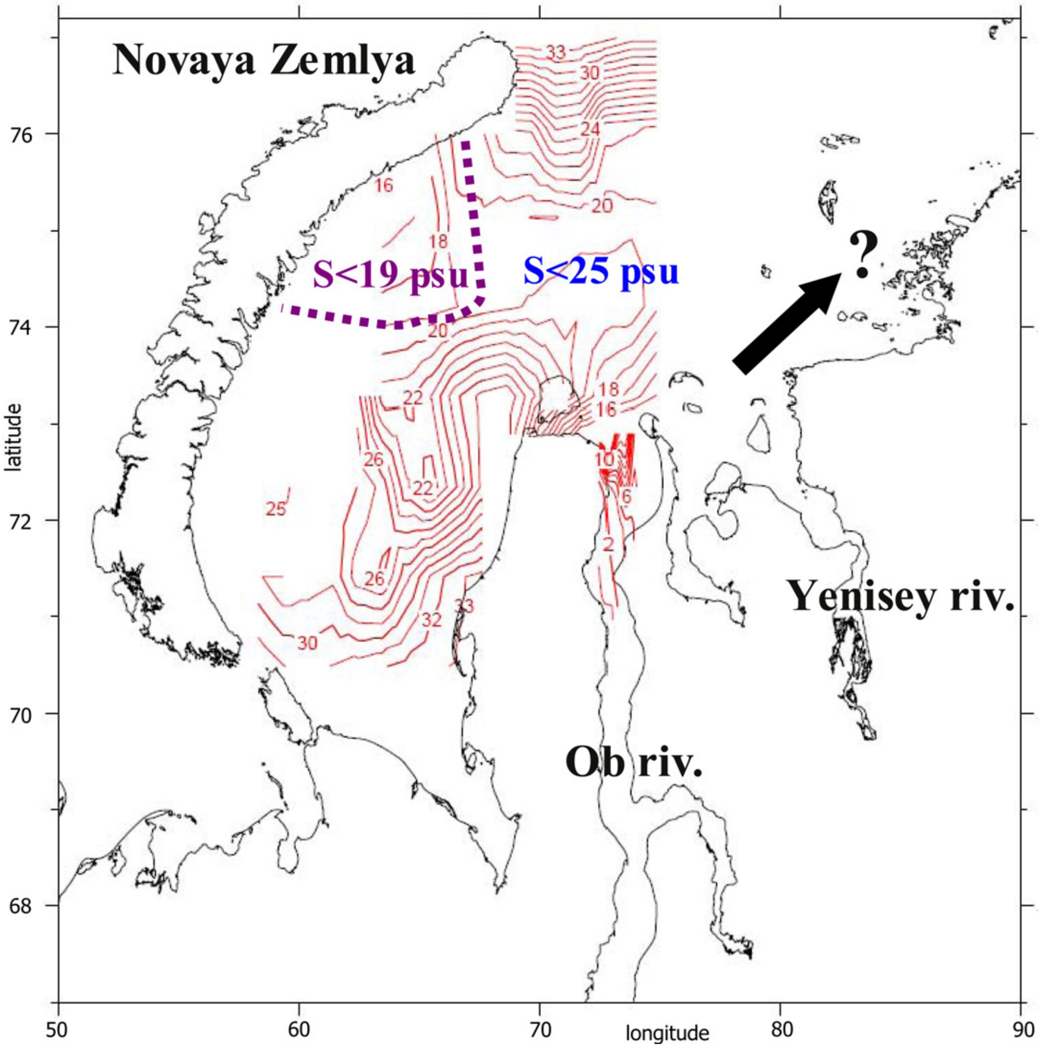


Fig. 3. Distribution of salinity in the upper layer over the south-western part of the Kara Sea in September, 2007.

## 2. Experimental set-up

A study of the physical mechanism for horizontal mixing of Ob' and Yenisei plumes in the Kara Sea was fulfilled by means of laboratory modeling (Fig. 4.) The experimental runs were provided in the circular tank with diameter 60 cm, filled by salt water (20 g/kg). The thickness of salt water layer $H$ was varying from 3 to 25 cm from one experimental run to the other. In order to reproduce the effects of Earth rotation the tank was displaced on the rotating platform. Some experimental runs were fulfilled at non-rotating platform. In the other experimental runs the platform was rotating with angular frequency $\boldsymbol{\Omega} = 0.4 – 1.3$ s$^{-1}$. Two horizontal silicon tubes with internal diameter 0.8 cm were connected to the reservoirs with fresh water. The tubes were fixed at the sidewall of the tank. They were directed toward the centre of the tank at a subsurface level of the salt water layer. To decrease an impact of the sidewall on the plume formation process thee ends of the tubes were putted forward from the sidewall to a distance of 10 cm. The angle between the tubes was 120°.

To visualize the mixing process the fresh water in reservoirs was colored by dye with different color. Particularly, we used blue color for one fresh water source and yellow color for the other. Small paper pellets were added to the surface of the water layer in the tank to visualize the fluid motion and to estimate the velocity of fluctuating currents. During every experiment the process of desalinated water plumes formation, their interaction and mixing with each other was recorded from above by video camera mounted at the rotating platform.

Before of each experimental run the salt water layer was at the state of immobility (non-rotating platform) or of solid body rotation (rotating platform). At the beginning of the run both sources of fresh water supply with equal and constant volume flux $\boldsymbol{Q} = 5\ \mathrm{cm}^3/\mathrm{s}$ were turned on. The turbulent jet-like flows were formed in front of the tubes. In the absence of platform rotation each jet was ending by symmetrical vortex dipole (Fig. 5). In the presence of platform rotation the anti-cyclonic eddies were formed at some distance from the ends of the tubes due to the Coriolis force effect (fig. 6a). These eddies were growing with time. After several periods of platform rotation – laboratory days (l.d.) they were splitting in two or more anticyclones due to baroclinic instability. Soon after that the plumes began to interact with each other (fig. 6c). The baroclinic eddies caused chaotic penetration of water from one plume to the other. After a fixed time interval, the sources of fresh water were turned off. The rest of the time the interaction and mixing of the plumes was continued without mass and momentum supply. Even in that case the interacting eddy-like plumes were growing with time until the tank area was entirely covered by UDL that consisted of differently colored water patches (fig.7 d). Finally the color homogeneity of UDL waters in the tank was achieved due to mixing produced by slowly decaying baroclinic eddies. It should be noted that in the absence of platform rotation mixing timescale was considerably less than in the presence of platform rotation.

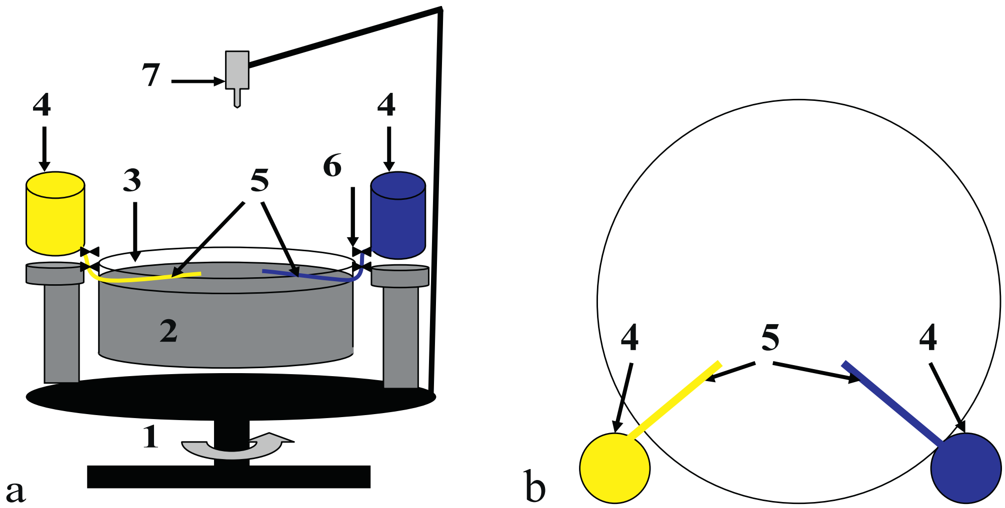


Fig. 4. Scheme of the laboratory set-up: a) side view: 1 – rotating platform; 2 – circular organic glass tank with not colored homogeneous salty water; 3 – lid of tank; 4 – source of yellow fresh water; 5 – source of blue fresh water; 6 – silicon tube; 7 – tap; 8 – videocamera. b) top view.

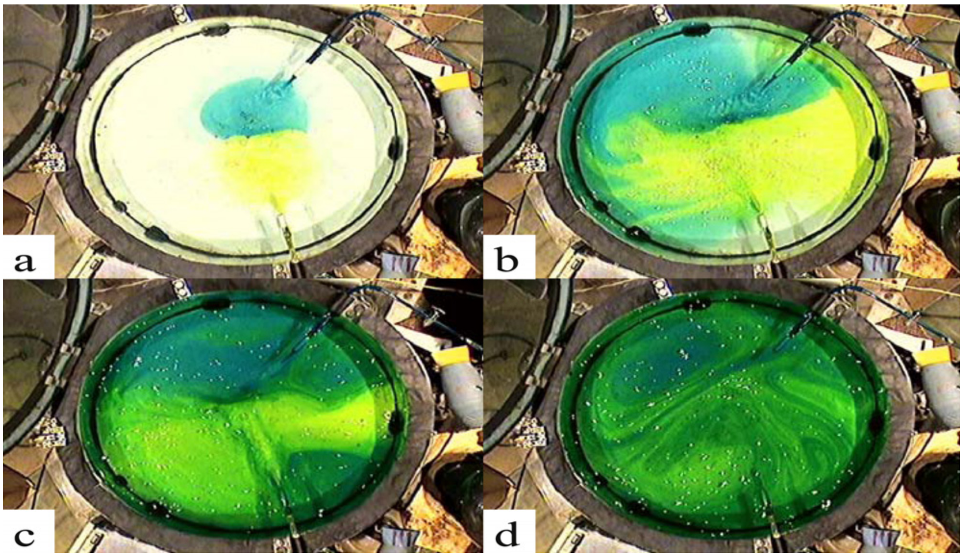


Fig. 5. The desalinated water plumes formation, their interaction and mixing in non-rotating fluid. Thickness of salt water layer $H = 14$ cm. The sources are active for 150 s and then – switched off. The pictures are taken after the time counted from the moment when sources are switched off: a) 15 s; b) 70 s; c) 150 s; d) 300 s.

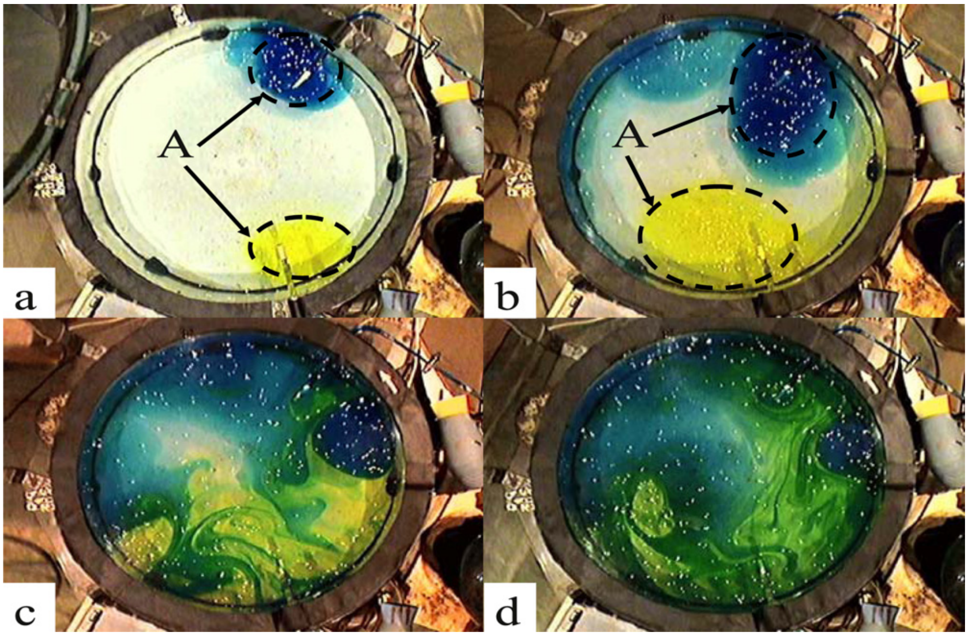


Fig. 6. The desalinated water plumes formation, their interaction and mixing in rotating fluid. Thickness of salt water layer – $H = 14$ cm. Period of platform rotation – $T = 5$ s. – The pictures are taken after the non-dimensional time $t/T_0$ counted from the moment when sources are switched on: a) 3; b) 14; c) 30; d) 60. Dotted line contours the anticyclonic eddies (**A**) formed by the source flow.

## 3. Results of the experiments

The processing of the experimental data allowed us to find the relation between the radius $\boldsymbol{R}$ of eddies and baroclinic deformation radios $\boldsymbol{R_d}$ (Fig. 7). This Figure shows that when $\boldsymbol{R_d} < 0.3\boldsymbol{R_0}$, $\boldsymbol{R} \approx \boldsymbol{R_d}$ and when $\boldsymbol{R_d} > 0.3\boldsymbol{R_0}$, $\boldsymbol{R} \approx 0.3\boldsymbol{R_0}$ and does not depend on $\boldsymbol{R_d}$.

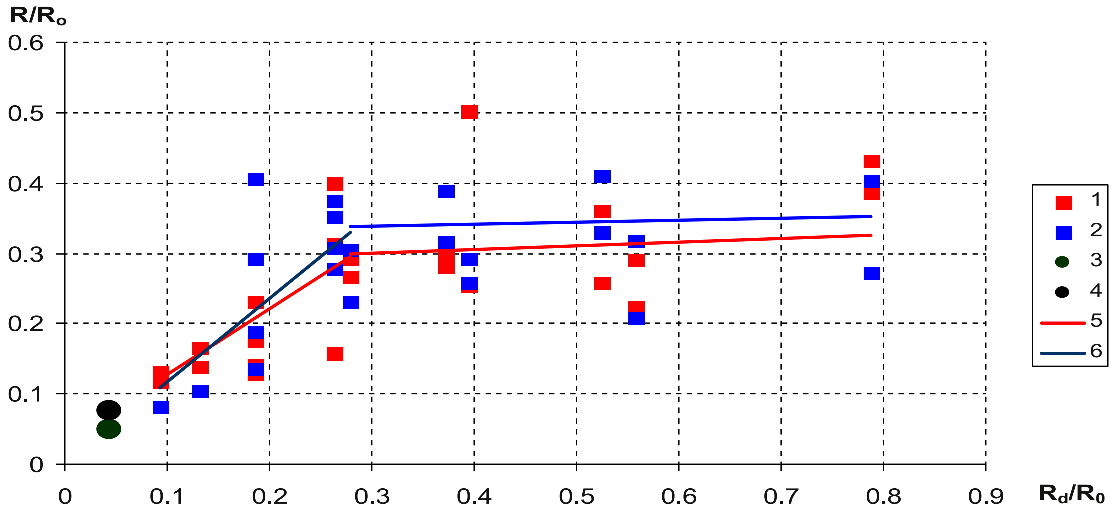


Fig. 7. Dependence radius R of eddies from baroclinic deformation radios. 1 – to yellow eddy; 2 – to blue eddy; 3 – eddy near Ob' mouth; 4 – eddy near Yenisey mouth; 5 – trend line to yellow eddy; 6 – trend line to blue eddy.

The most important task of this work is an estimation of the time scale $\boldsymbol{T_m}$ for horizontal mixing of the interacting plumes and its dependence on $\boldsymbol{R_d}$.

Let us assume that the mesoscale eddy field related with interacting fresh water plumes is stationary for intermediate assimptocic (generally, after the supply is switched off it is decaying, but due to a continuation of baroclinic instability the mesoscale eddy energy could be constant for the enough long time interval). According to previous consideration $\boldsymbol{K \sim (\langle U'^2 \rangle)^{1/2} R_d}$ – the coefficient of horizontal exchange and $\boldsymbol{(\langle U'^2 \rangle)^{1/2}}$ – r.m.s. velocity of mesoscale eddies. From the Froude number constancy for forming baroclinic eddies [5] – $\boldsymbol{Fr = (\langle U'^2 \rangle)^{1/2}/(g'H)^{1/2} = (\langle U'^2 \rangle)^{1/2}/R_d f = const}$, we obtain: $\boldsymbol{K \sim R_d^2 f}$. Using the expressions $\boldsymbol{T_m \approx R_0^2/2K}$ and $\boldsymbol{T_0 = 2\pi/\Omega = 4\pi/f}$ we obtain:

$$T_m/T_0 \sim R_0^2/R_d^2\,,$$

where $\boldsymbol{R_0^2/R_d^2}$ – is the Burger number. This expression was checked on the base of the data from the laboratory experiments.

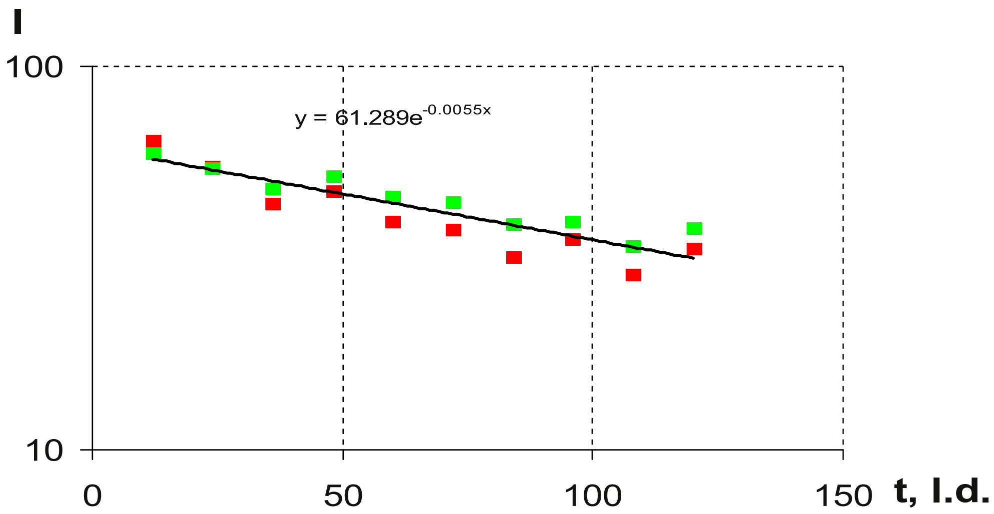


Fig. 8. Root mean square of the fluctuating values of the concentration of two colors – red and green, determined at many points of the tank surface for different moments of time ; line – trend line.

**Table 1.** The values of non-dimensional mixing time scale $\boldsymbol{T_m}$ at different values square non-dimensional $R_d$

| square non-dimensional $R_d$ $\boldsymbol{R_0^2/R_d^2}$ | visualization estimate scale $T_m/T_0$ | quantitative estimate scale $T_m/T_0$ |
|---|---|---|
| 1.6 | 40 | 42 |
| 3.2 | 40 | 42 |
| 6.4 | 36 | 24 |
| 13 | 40 | 39 |
| 15 | 84 | 64 |
| 29 | 84 | 60 |
| 58 | 180 | 108 |
| 116 | 180 | 181 |

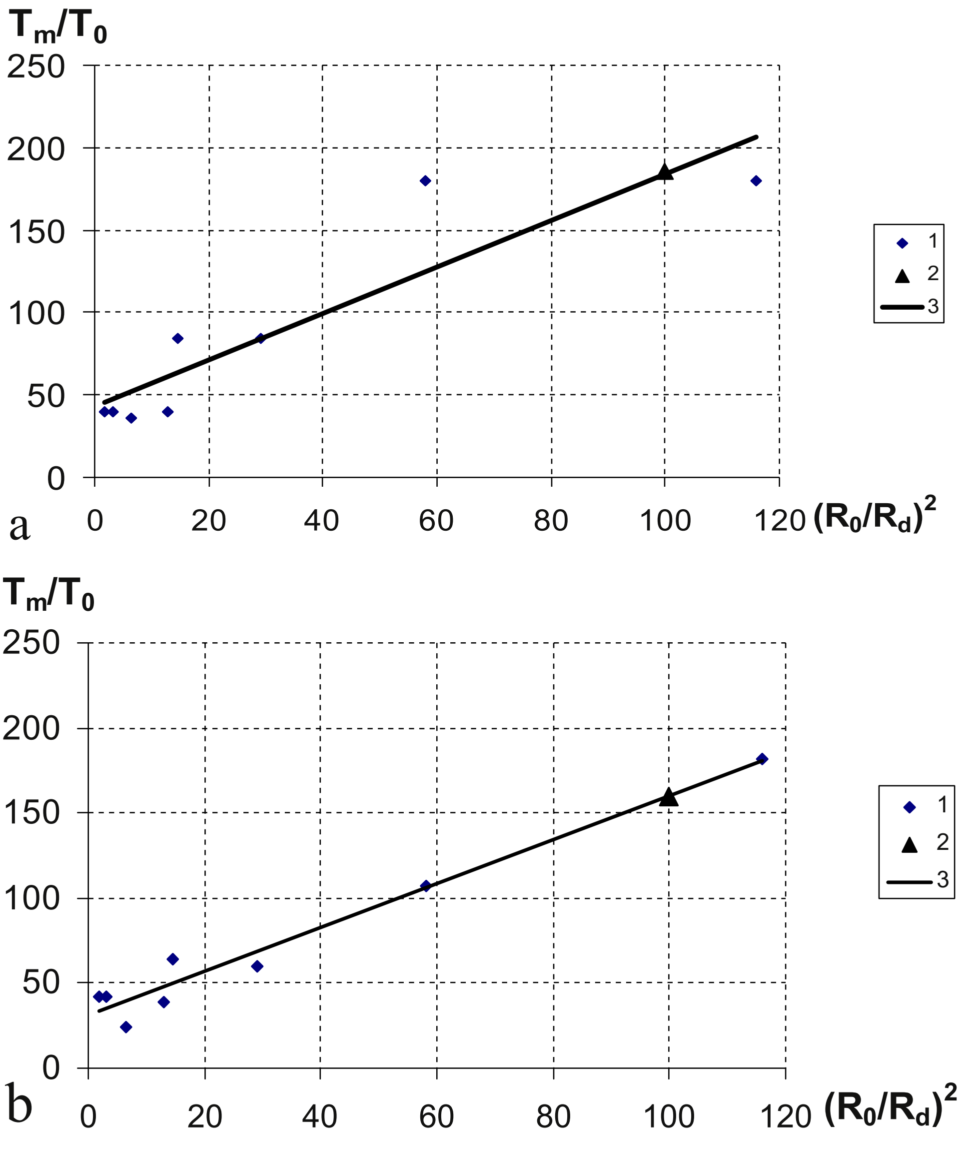


Fig. 9. The dependence of non-dimensional mixing time scale on the Burger number: a) visual estimate of the timescale $T_m$; b) quantitative estimate of the timescale $T_m$. 1 – laboratory data; 2 – estimate for the Kara Sea; 3 – trend line.

The mixing timescale $T_m$ was estimated using two different methods: visually, and on base of quantitative estimation of space homogeneity of water colour distribution over the surface of fluid in the laboratory tank recorded by video camera. The first method is qualitative and focuses on determining of the moment, when color of water in the tank becomes homogeneous. The second – quantitative method is based on the analysis of color structure of interacting plumes on video image using special computer programs. This method allows to compute the fluctuations in colour concentrations at many points over the surface of fluid in the tank and to compute their root mean square value. This value $\boldsymbol{I}$ is decreasing with time more or less exponentially: $\boldsymbol{I(t) = I(0)\, e^{-at}}$ (Fig. 8) where $\boldsymbol{I}$ is a rout mean square value of the fluctuating colour concentration in different point of the tank. The time scale of horizontal mixing of differently colored fresh water plumes may be estimated as $\boldsymbol{T_m = 1/a}$. This parameter was determined for all experimental runs.

The values of non-dimensional mixing time scale $\boldsymbol{T_m/T_0}$ determined by two methods described above and corresponding values of $\boldsymbol{R_0^{2}/R_d^{2}}$ are presented in the ***Table 1***. It follows from ***Table 1.*** that both methods give nearly the same results. From Fig. 9, where $\boldsymbol{T_m/T_0}$ is plotted versus $\boldsymbol{R_0^{2}/R_d^{2}}$, it follows that the dependence between these parameters is close to linear. If we apply the results of the experiment to the Kara Sea conditions the time scale for horizontal mixing of Ob' and Yenisei interacting plums should be about 150 – 200 days. These values seem to be realistic and consistent with previous estimate.

The results of the laboratory experiment confirm the observations that the UDL waters in Kara sea are not well horizontally mixed and consist of the "parcels" containing predominantly the fresh water of Ob' or Yeniseyi origin.

The basic conclusion following from this work is that horizontal mixing between the interacting largescale ($\boldsymbol{R_0 >> R_d}$) freshwater plumes in the sea (such the Ob' and Yenisei river plumes) is strongly controlled by Earth rotation. By means of the laboratory experiment it is shown that:

a) the radius $\boldsymbol{R}$ of mesoscale eddies in the plumes is proportional to the baroclinic radios of deformation $\boldsymbol{R_d = (g'H_o)^{0.5}/f}$;

b) the time scale $\boldsymbol{T_m}$ of mixing process is proportional to $\boldsymbol{R_d^{-2}}$.

## Acknowledgements

The work was supported by the Program № 23 of Russian Academy of Sciences.

## References

[1] Harms IH, Karcher MJ. Modeling the seasonal variability of circulation and hydrography in the Kara Sea. *J.Geophys. Res.* 1999;**104**(C6):13431–8.
[2] Zatsepin AG, Zavialov PO, Kremenetskiy VV, Poyarkov SG, Soloviev DM. The upper desalinated layer in the Kara Sea. *Oceanology* 2010;**50**(5):698 – 708.
[3] Makkaveev PN, Stunzhas PA, Khlebopashev PV. On determination of Ob' and Eniysey river waters in the semifresh lenses at the Kara Sea in 1993 and 2007. *Oceanology* 2010;**50**(5):740 – 7.
[4] Zhurbas VM, Zatsepin AG, Grigor'eva YuV, Eremeev VN, Kremenetskiy VV, Motyzhev S et al. Water circulation and characteristics of currents of different scales in the upper layer of the Black Sea from drifter data. *Oceanology* 2004;**44**(1):34 – 48.
[5] Griffiths RW, Hopfinger ES. The structure of mesoscale turbulence and horizontal spreading of ocean fronts. *Deep-Sea Res.* 1984;**31**(3):245 – 69.